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Limits on the Viscosity to Entropy Density Ratio from PHENIX Data on Single Electron Production

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Abstract. The ratio of shear viscosity η to entropy density s is a key measure of the damping in any fluid. By requiring a simultaneous description of the energy loss ($R_{AA}(p_T)$) and flow ($v_2(p_T)$) of single electrons from semi-leptonic decays of heavy flavor produced in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions, the PHENIX experiment obtained an estimate $\eta/s \approx (1.3 - 2)(1/4\pi)$ [1], that is, near the conjectured bound [2] of $1/4\pi$. The PHENIX result is compared to other estimates for η/s in Au+Au collisions. Prospects for an improved understanding of the extraction of η/s from various heavy ion data are presented, along with a brief discussion of current theoretical challenges in modeling viscous effects.

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1. Introduction

The strong elliptic flow patterns discovered at RHIC, together with their detailed dependence on particle mass and on transverse momentum, are well-described by ideal hydrodynamic calculations which ignore viscous effects. However, as noted by Danielewicz and Gyulassy [3], straightforward arguments based on the uncertainty principle suggest that the viscosity for any thermal system must be non-zero. This observation was extended by Kovtun, Son and Starinets (KSS) [2], who demonstrated that conformal field theories with gravity duals have a ratio of viscosity η to entropy density s of $1/4\pi$ (in natural units). KSS conjectured that this value is a bound for any relativistic thermal field theory, that is, $\eta/s \geq 1/4\pi$. Estimates for the value of this ratio in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV based on flow [4, 5], fluctuations [6], entropy production [7] and detailed hydrodynamic calculations [

8, 9] all suggest that η/s for the QGP created in these collisions can not exceed the KSS bound by more than a factor of ~ 4.

All of the estimates mentioned above focus on observables related to bulk phenomena generated by the light quarks and/or gluons. The dynamics of heavy flavor produced in the medium is also sensitive to the viscosity to entropy density ratio, but with significant differences expected as compared to the light quark observables, due to the large masses of charm ($m_c \sim 1.3$ GeV) and bottom ($m_b \sim 4.2$ GeV) quarks relative to the 0.2-0.4 GeV temperature scale. It is both an experimental and a theoretical challenge to determine the flow and energy loss of heavy flavor and to relate these observables to the properties of the bulk medium.

2. Experimental Method

The PHENIX experiment [10] was designed to measure heavy flavor production via the semi-leptonic decay of mesons containing charm or bottom quarks. This may be done via the detection of either 'single muons' or 'single electrons'; in this work we concentrate on the latter. The isolation of those electrons[1] from the decay of D and B mesons requires good momentum resolution, excellent electron identification, stringent control of mass in the detection aperture (to reduce background from conversion pairs) and superb understanding of the background from conversions (both external conversions and 'internal' conversions from Dalitz decays). PHENIX determines the momentum of charged particles with drift and pad chambers covering the region[2] $|\eta| < 0.35$. Electron candidates are found by requiring a match between the charged track and clusters in a Cerenkov counter. These candidates must also have a good match between the momentum p from the tracking system and the energy E as measured by electromagnetic calorimeters. Backgrounds from conversions are reduced by minimizing the mass between the beryllium beampipe and the first tracking detector; a He-bag is introduced for this purpose. The remaining backgrounds are both calculated, using a 'cocktail' consisting of all known sources of electrons, and measured, by special 'converter' runs in which the change in electron yield from additional material introduced around the beam pipe allows an extrapolation to the limit of zero external conversions.

3. Experimental Results

In a series of measurements at center-of-mass energy of 200 GeV, the PHENIX Collaboration determined the transverse momentum spectrum and total cross section for charm production [3] in p+p collisions [11]; demonstrated that in Au+Au collisions the yield of electrons from heavy flavor obeyed binary scaling at low transverse

[1] Here 'electrons' is shorthand for both electrons and positrons.

[2] Note that in this sentence only, the symbol 'η' refers to pseudorapidity rather than viscosity.

[3] Note that in addition to the two methods of background determination mentioned in Section 2 this work provided a third (consistent) determination of the background using $e\gamma$ coincidences; see Figure 3 of Ref. [11].

momenta but showed substantial suppression at high transverse momenta [12]; observed a non-zero elliptic flow for single-electrons in Au+Au collisions [13]; showed that the higher statistics Run-5 p+p data on single electron production were well-described within errors by a fixed-order plus next-to-leading-log (FONLL) pQCD calculation [14] over the broad range $0.3 < p_T < 9$ GeV/c [15]; and used the higher statistics Run-4 Au+Au data set to extend the measurements of single electron energy loss and elliptic flow, and compared these results to models to extract an estimate for the allowed range of η/s [1]. Together, these studies have established a consistent picture of heavy flavor production at RHIC energies, in which charm and bottom are produced in both p+p and Au+Au collisions at a rate consistent with pQCD, but with charm and perhaps even bottom quarks losing energy and flowing with the medium produced in Au+Au collisions.

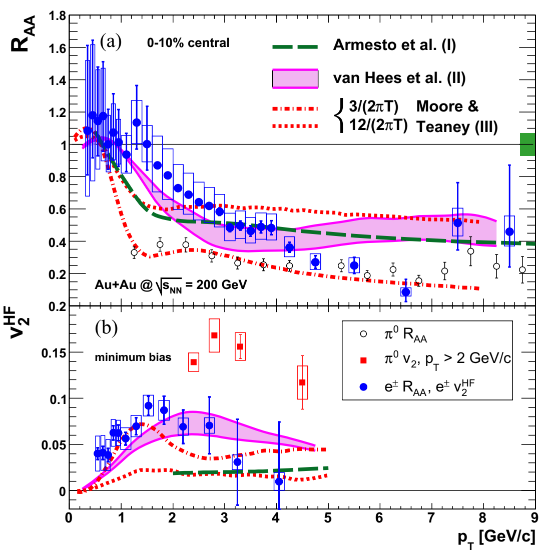

Fig. 1. PHENIX results [1] from $\sqrt{s_{NN}} = 200$ GeV collisions for the nuclear modification factor R_{AA} (top panel, for the 10% most central collisions) and elliptic flow parameter v_2 (bottom panel, for minimum bias collisions) as a function of electron p_T. Data are also shown for the π^0 suppression factor [16] and the π^0 v_2 [17]. The predictions of three models [18, 19, 20] for these quantities are also shown.

The PHENIX Run-4 results on single electron energy loss and flow are compared to the calculations of three models in Figure 1. With appropriate selection of parameters, the perturbative calculations of both Armesto *et al.* [18] and those of Moore and Teaney [20] can describe the magnitude and shape of the nuclear modification factor $R_{AA}(p_T^e)$. However, neither approach reproduces the large v_2 flow parameter observed in the data. In contrast, the model of van Hees, Greco and Rapp [19] which explicitly assumes the existence of heavy quark resonances in a strongly-coupled quark-gluon plasma is in reasonable agreement with both the nuclear modification factor and the flow parameter over the entire measured range of electron transverse momentum.

This last observation provides a straightforward, albeit indirect, method to infer the ratio of viscosity to entropy density. The resonance model employed in Ref. [19] leads to an estimate for the heavy quark spatial diffusion constant $D_s \sim (4-6)/2\pi T$ for temperatures T in the range 0.2 GeV $< T <$ 0.4 GeV(see Figure 23 of Ref. [21]). Moore and Teaney [20] perform a perturbative calculation of this quantity, and find that for a medium with three light flavors the ratio of D_s to the hydrodynamic diffusion constant $\eta/(\epsilon+p)$ for the bulk (ϵ is the energy density and p the pressure of the medium) has a value of ~ 6 roughly independent of the coupling strength $\sim m_D/T$, where m_D is the Debye mass. They argue that the weak variation with coupling strength is to be expected in this *ratio* of transport coefficients, making it plausible that it remains near 6 in the strongly-coupled regime. In this case, and approximating the thermodynamic identity $\epsilon+p = Ts+\mu_B n_B \approx Ts$ appropriate for the baryon-free central region, one readily finds $\eta/s \sim (1.33-2)/4\pi$, that is, a value near the KSS bound and consistent with other estimates for the RHIC plasma.

4. Discussion

New data from PHENIX indicates that the flow of single electrons persists to trans-

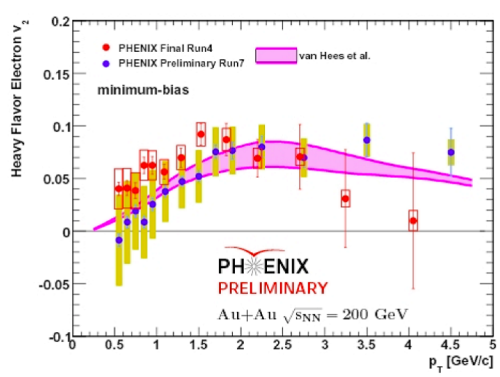

Fig. 2. Published [1] and preliminary PHENIX results [22] for the elliptic flow parameter v_2 as a function of electron transverse momentum in minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV collisions, together with predictions from the resonance model of van Hees, Greco and Rapp [19].

verse momenta as large as 4 GeV/c, as shown in Figure 2. This is the momentum region in which FONLL calculations [14] indicate that the yield of electrons from bottom quarks becomes comparable to or greater than that from charm quarks.

Given the substantial (and surprising) coupling of charm quarks to the medium at

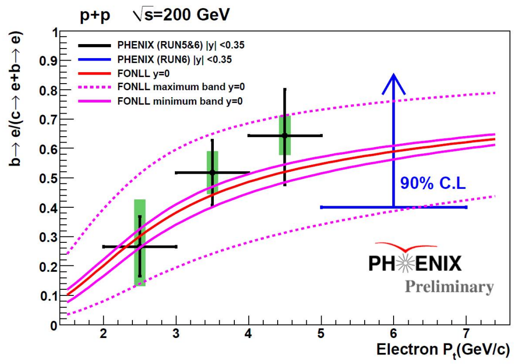

Fig. 3. Preliminary PHENIX results [23] for the fractional contribution of b quarks to single electron yields as a function of electron transverse momentum in 200 GeV p+p collisions.

RHIC, it is of significant interest to determine if this is also the case for bottom quarks, since all perturbative calculations based on $m_b \gg T$ suggest otherwise. A necessary first step in this direction is the determination of the b/c ratio as a function of p_T in p+p collisions. As shown in Figure 3, preliminary results from PHENIX [23] obtained via electron-hadron correlations for this quantity are consistent with the predictions of FONLL calculations [24]. Naively, this would imply that the significant flow and suppression seen in single electrons for $p_T \sim 4$ GeV/c results from the strong coupling of bottom quarks to the medium. However, a proper accounting of the very large uncertainties in Figure 3 shows that no such 'strong' conclusions may be drawn from the data at this time [25]. Definitive statements must await improved analyses with the current data sets, and upgraded vertex detection capabilities that will enhance the ability to separate D and B decay products. Nonetheless, it is intriguing to note that very recent work by Kharzeev [26] argues that even bottom quarks would be subject to a universal upper bound on their energy. There is therefore very considerable intellectual value in disentangling the energy loss of b and c quarks, as a clear demonstration of strong coupling of massive b quarks to the QGP would be yet another surprise in the ongoing sQGP paradigm shift.

5. Conclusions

The PHENIX experiment has made a series of definitive measurements validating the utility of pQCD calculations of heavy flavor production systematics in p+p collisions at RHIC energies, and demonstrating that heavy quarks lose significant energy and flow with the medium created in Au+Au collisions. These observations, combined with model calculations, indicate that the viscosity to entropy density is near or at the bound of $1/4\pi$ conjectured by Kovtun, Son and Starinets [2]. It will be essential in the years ahead to determine separately the coupling of b and c to the sQGP created in Au+Au collisions at RHIC.

Acknowledgments

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